AAAS
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The Physics of Neutrinos

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Neutrinos are Abundant

We, and all the everyday objects around us here on earth, are made of electrons, protons, and neutrons.

In the universe, there are ~ 10^9 neutrinos for every electron or proton or neutron.

Neutrinos are among the most abundant particles in the universe.

If we wish to understand the universe, we must understand the neutrinos.

The Leptons and their Flavors

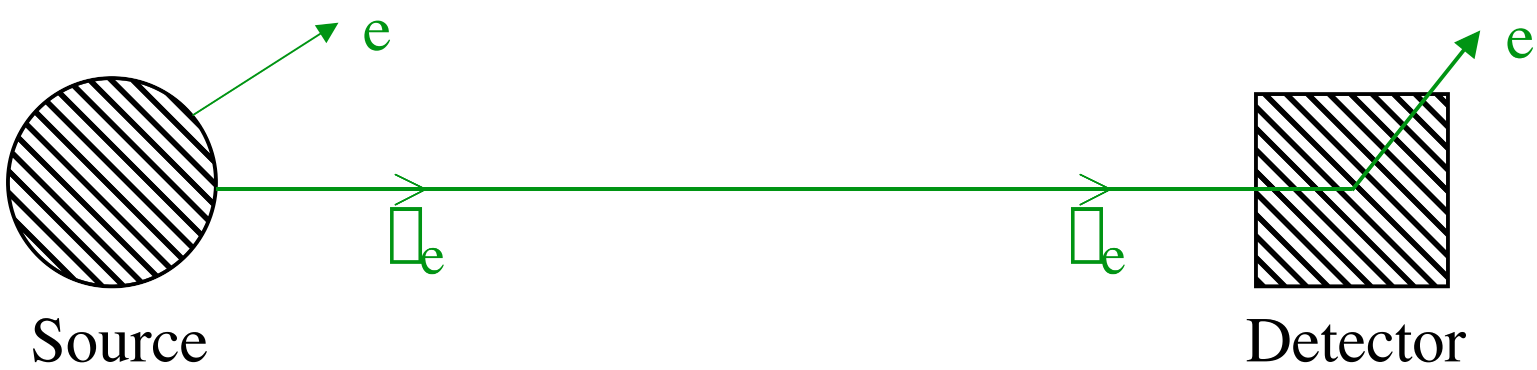
Charged Lepton	Mass	Associated Neutrino
Electron (e)	1	$\square_e$
Muon (□)	207	$\square_{\square}$
Tau (□)	3480	$\square_{\square}$

What does "associated" mean?

A neutrino is created together with a charged lepton.

When a neutrino interacts with a detector, it creates a charged lepton.

The neutrino and charged lepton flavors match:



But not —

The Discovery of Neutrino Mass

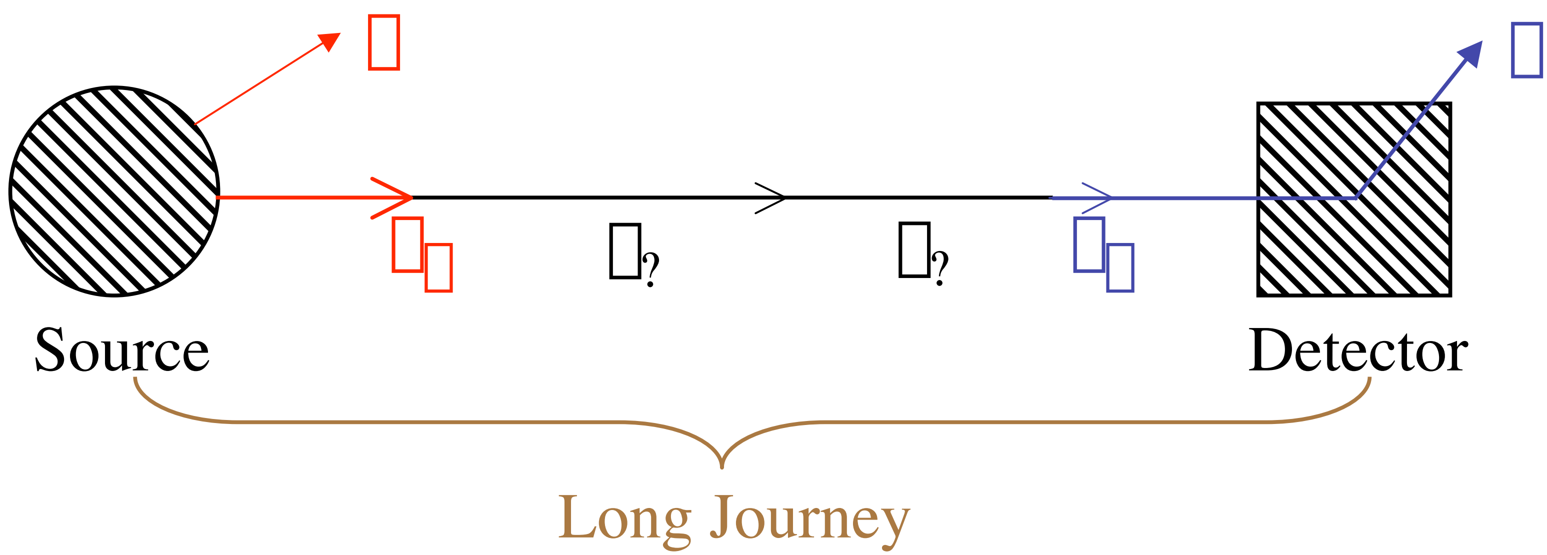
Neutrinos have long been known to be extremely light — perhaps massless.

It has now been discovered that they do have nonzero — if tiny — masses.

This discovery raises many questions we must answer.

How Was Neutrino Mass Discovered?

It has been found that, given enough time, a neutrino can change from one flavor to another:



While traveling, has morphed into .

This change of flavor is made possible by neutrino mass.

When neutrinos have masses, $\square_{\square}$ and $\square_{\square}$ are not particles of definite mass.

Rather, they are mixtures of such particles.

Example —

$$\square_{\square} = (\cos \square)\, \square_{\text{Light}} + (\sin \square)\, \square_{\text{Heavy}}$$

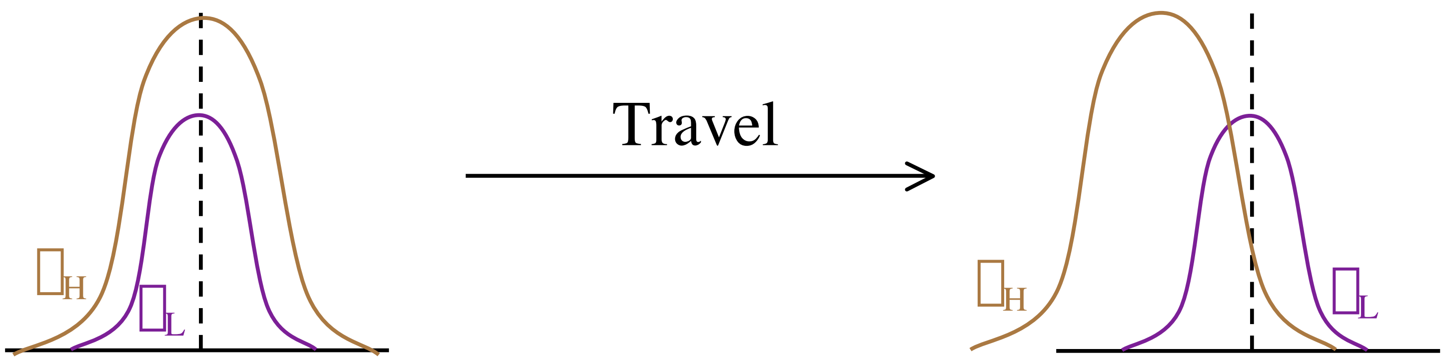
$$\square_{\square} = (-\sin \square)\, \square_{\text{Light}} + (\cos \square)\, \square_{\text{Heavy}}$$

Mixing angle

Neutrinos of definite mass

In quantum mechanics, uncertainty rules.

A neutrino behaves like a wave.



At birth a □□

Later

As the neutrino travels with a given energy E, its heavier □H part falls behind.

As a result, the neutrino is not a □□ anymore, but a mixture of □□ and □□. Maybe □□ and maybe □□.

In quantum mechanics, uncertainty rules.

Probability $[\nu_{\square} \to \nu_{\square}] =$

ν_H mass

ν_L mass

Speed of light

Distance traveled

$$= \sin^2 2\theta \, \sin^2 \left[6.5 \times 10^{15} \left(\frac{L}{1\ \text{km}} \right) \left(\frac{m_e c^2}{E} \right) \left(\frac{m_H^2 - m_L^2}{m_e^2} \right) \right]$$

Mixing angle

Neutrino energy

Electron mass

Neutrino Oscillation

Experiments are sensitive to $\left(\frac{m_H^2 - m_L^2}{m_e^2} \right)$ even smaller than

$$\frac{1}{100{,}000{,}000{,}000{,}000} \,.$$

Only (Mass)^2 splittings are probed.

Evidence for Flavor Change

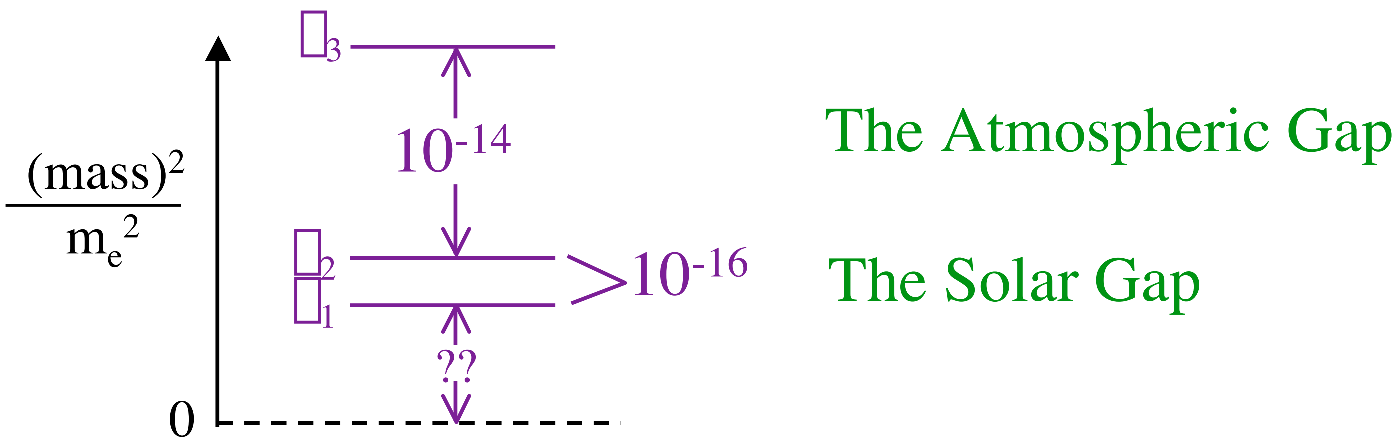
(Following talks)

Neutrinos	Flavor Change	Strength of Evidence
Solar	$\nu_e \rightarrow \nu_\mu$ and/or ν_τ	Compelling
Reactor (L ~ 180 km)	$\bar{\nu}_e \rightarrow$??	Very Strong
Atmospheric	$\nu_\mu \rightarrow \nu_\tau$	Compelling
Accelerator (L ~ 250 km)	$\nu_\mu \rightarrow$??	Interesting
Muon Decay ("LSND")	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Unconfirmed

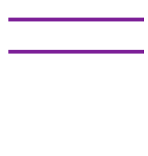
What Have We Already Learned?

There are at least 3 neutrinos of definite mass.

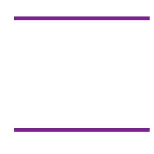
They are called ν_1, ν_2, and ν_3, and account for all observed flavor changes except the one reported by the Liquid Scintillator Neutrino Detector (LSND).



The spectrum could be



instead of



.

The LSND oscillation requires a splitting

$$\frac{m_H{}^2 - m_L{}^2}{m_e{}^2} \sim 10^{-11} \ .$$

Thus, confirmation of LSND would teach us that there are at least 4 neutrinos of definite mass: $\square_1$, $\square_2$, $\square_3$, $\square_4$.

But there are only 3 electron-like particles: e, □, □.

The only forces of nature experienced by neutrinos are gravity and the weak nuclear force (responsible for many radioactive decays).

A neutrino cannot experience the weak nuclear force unless it has an electron-like partner.

Out of ν_1, ν_2, ν_3, ν_4 we can make 4 distinct mixtures:

ν_e — e

ν_μ — μ

ν_τ — τ

ν_s — ??

Among the known forces of nature, only gravity would be experienced by ν_s, a sterile neutrino.

Confirmation of LSND $\Rightarrow$ very ghostlike neutrinos.

The Future — Open Questions

* How many neutrinos of definite mass exist?

3? 4? 17? ?

The world may have more than 3 spatial dimensions.

Perhaps the extra ones have been invisible so far because they are very small, and because only special particles, like the sterile neutrinos, can travel in them.

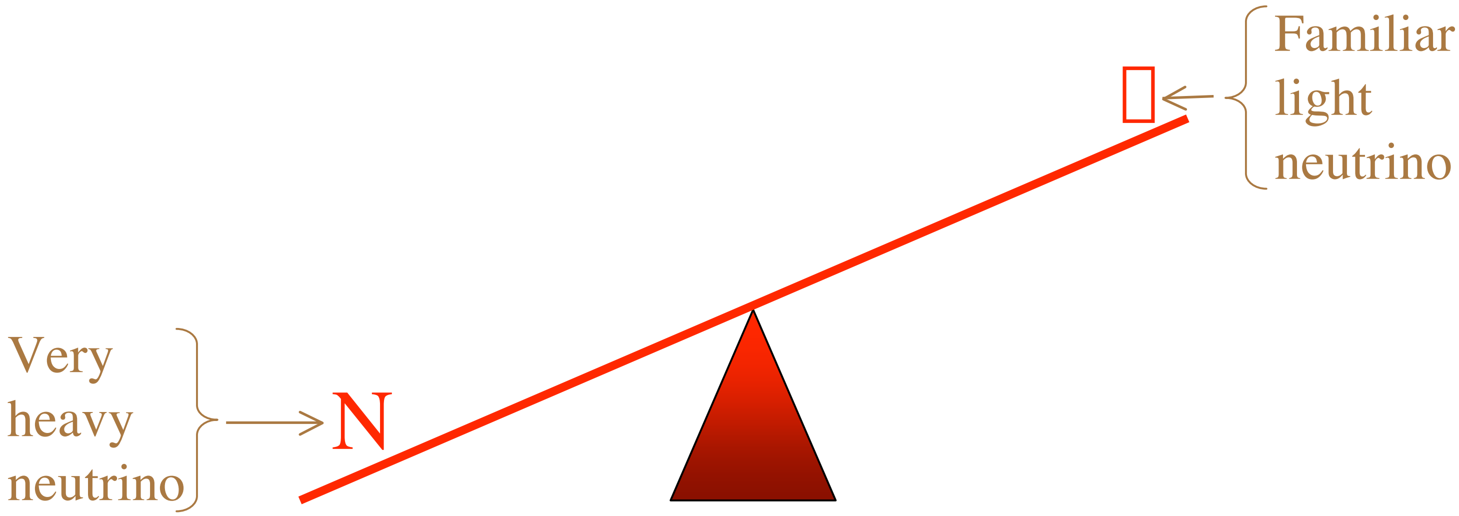
Motion in an extra dimension we cannot see would look to us like extra mass.

Extra dimensions □ Infinitely many neutrinos with different masses.

* Why are neutrinos so much lighter than the other particles?

The most popular proposed explanation is the —

See-Saw Mechanism



The see-saw mechanism predicts —

- Very heavy neutrinos N
- Neutrinos are their own antiparticles

* Are neutrinos their own antiparticles?

For every particle p, there is a corresponding antiparticle, $\overline{p}$.

$\overline{e^-} = e^+ \neq e^-$ since Charge (e^+) = -Charge (e^-).

Similarly for the quarks, the other constituents of ordinary matter.

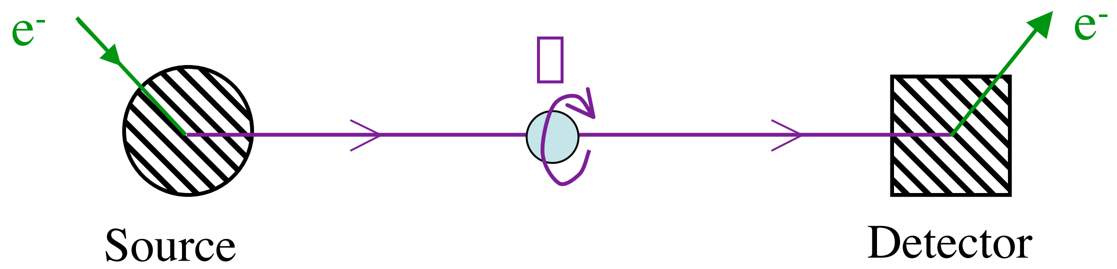
But neutrinos carry no electric charge.

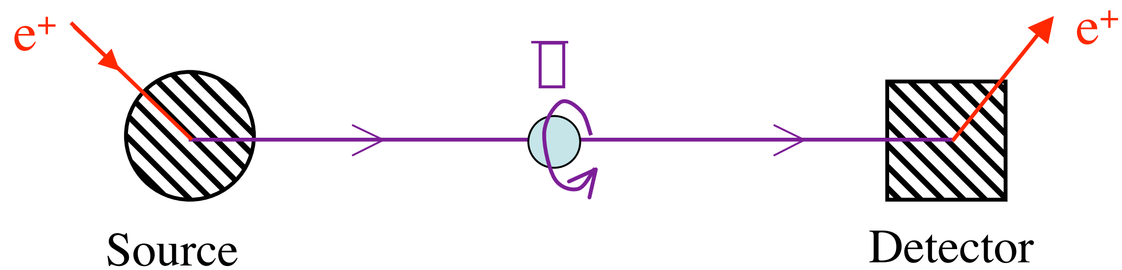
Do neutrinos carry some charge-like attribute that distinguishes a □ from a □?

The see-saw theory and other theoretical arguments say no.

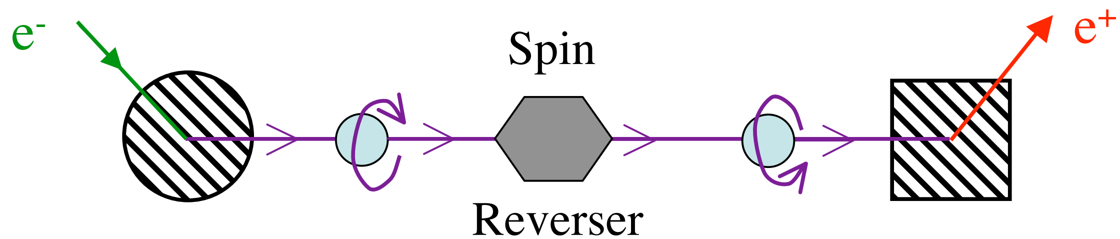
If this is right, neutrinos are very different from electrons and quarks.

How to Tell Whether $\bar{\nu} = \nu$

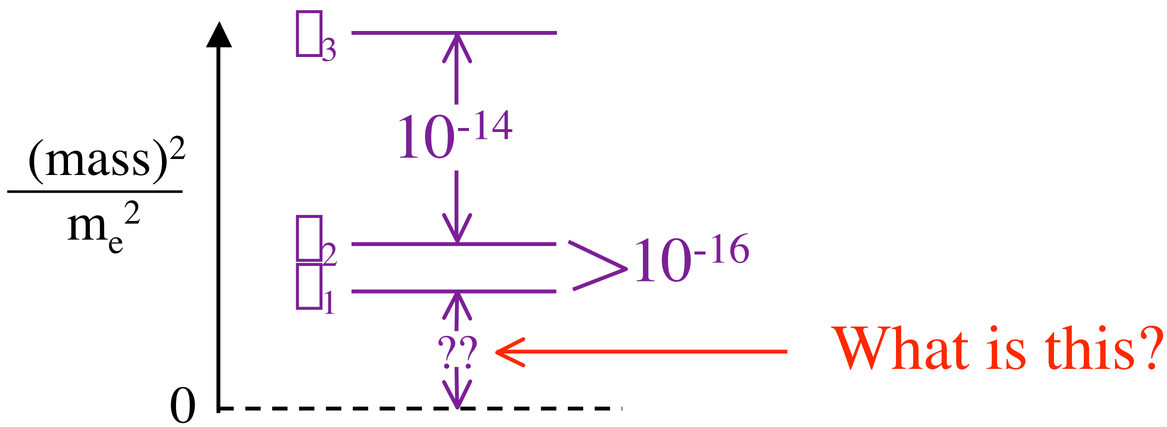




If, for a given direction of spinning, $\bar{\nu} = \nu$, then we can have



* How much do the neutrinos of definite mass weigh?



Neutrino mass influenced the formation of large-scale structure in the universe.

Perhaps studies of this structure can provide information on the scale of neutrino mass.

Indeed, they already have!

* Are neutrinos the reason we exist?

The universe contains MATTER, but essentially no antimatter.

Good thing for us:

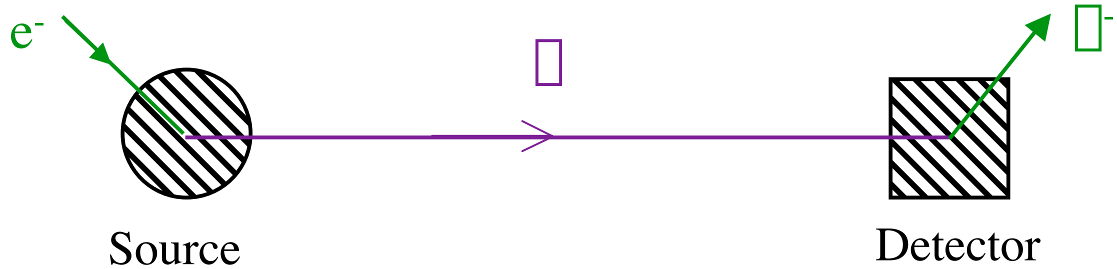
This preponderance of MATTER over antimatter could not have developed unless the two behave differently.

Could the interactions of MATTER and antimatter with neutrinos provide the crucial difference?

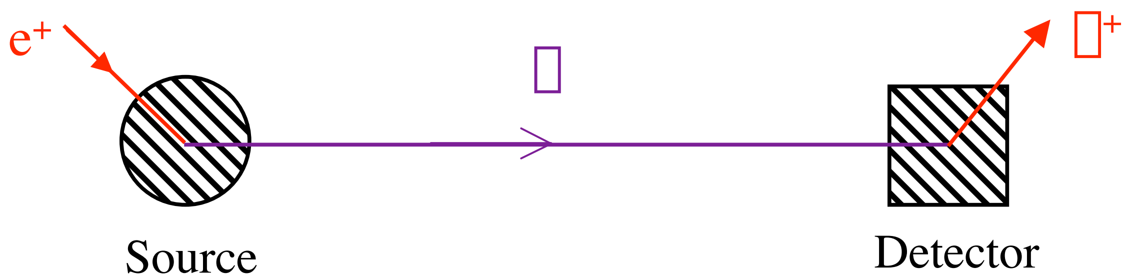
Assume the see-saw picture is right:

- □ = □
- There are very heavy neutrinos N

A neutrino flavor change involving **MATTER**:



A neutrino flavor change involving antimatter:



Perhaps these two flavor changes have different probabilities.

If they do, it is likely that

Probability [N $\rightarrow$ $\underset{\text{MATTER}}{e^-}$ + …] $\neq$ Probability [N $\rightarrow$ $\underset{\text{antimatter}}{e^+}$ + …]

in the early universe.

This phenomenon (leptogenesis) would have led to a universe containing unequal amounts of **MATTER** and antimatter.

If N decays led to the present preponderance of **MATTER** over antimatter, then we are all descendants of heavy neutrinos.

Conclusion

Beautiful experiments have led to the discovery of neutrino mass.

This discovery has raised very interesting questions that we must now try to answer.